On Separate Chemical Freeze-outs of Hadrons and Light (anti)nuclei in High Energy Nuclear Collisions

Kyrill Bugaev, B. Grinyuk, A. Ivanytskyi, V. Sagun, D. Savchenko, G. Zinovjev

Bogolyubov ITP, Kiev, Ukraine

E. Nikonov

Laboratory for Information Technologies, JINR, Dubna, Russia

L. Bravina, E. Zabrodin

University of Oslo, Oslo, Norway

S. Kabana

University of Nantes and SUBATECH, Nantes, France

D. Blaschke

University of Wroclaw, Wroclaw, Poland

A. Taranenko

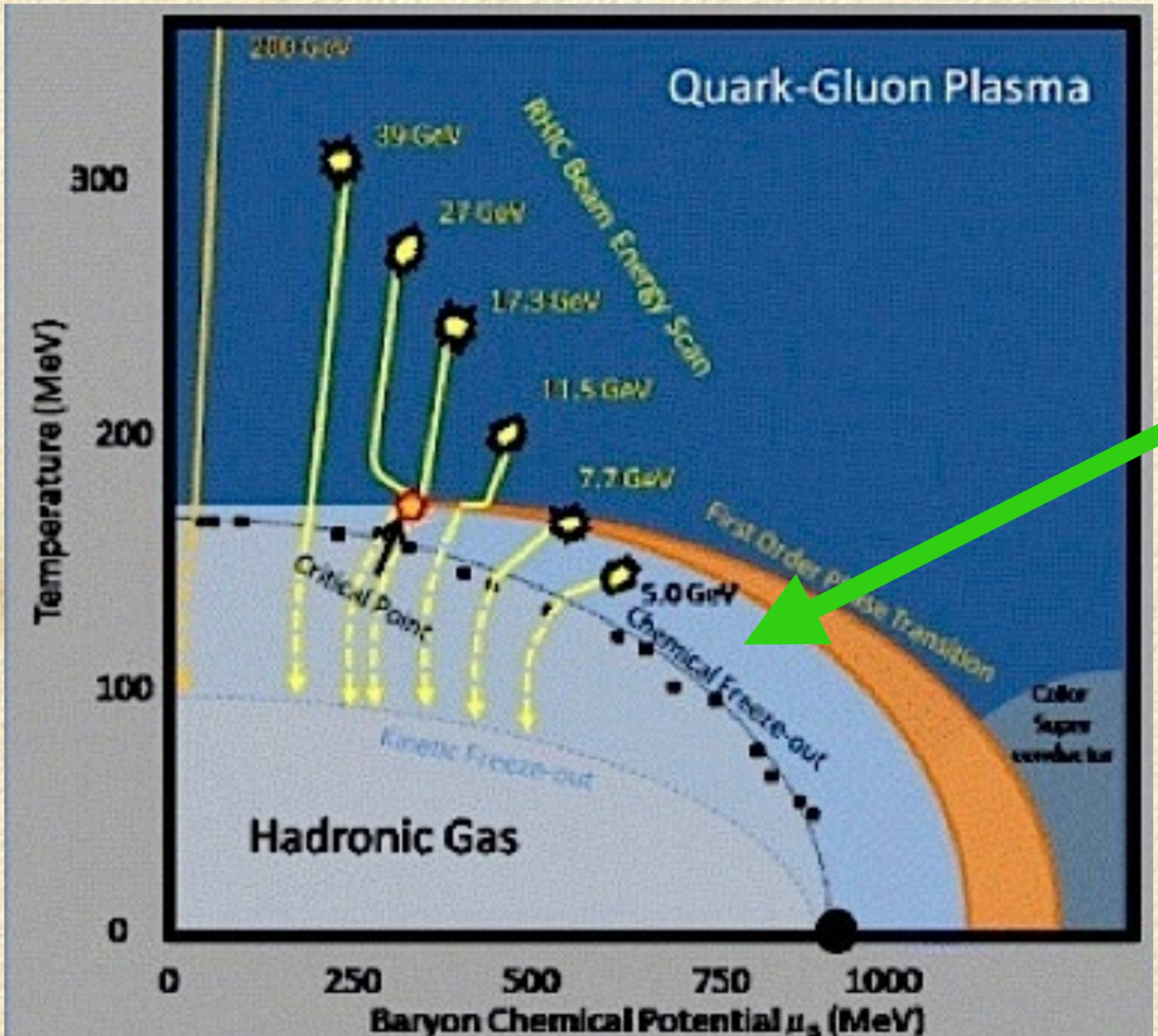
MEPhI, Moscow, Russia

Moscow, October 23, 2018

HRG: a Multi-component Model

HRG model is a truncated Statistical Bootstrap Model with the excluded volume correction a la VdWaals for all hadrons and resonances known from Particle Data Group.

For given temperature T, baryonic chem. potential, strange charge chem. potential, chem. potential of isospin 3-rd projection => thermodynamic quantities => all charge densities, to fit data.



Chemical freeze-out - moment after which hadronic composition is fixed and only strong decays are possible. I.e. there are no inelastic reactions.

Induced Surface Tension EOS

pressure

$$\frac{p}{T} = \sum_i \phi_i \exp\left(\frac{\mu_i - pV_i - \Sigma S_i}{T}\right)$$

new term

induced surface tension

$$\frac{\Sigma}{T} = \sum_i R_i \phi_i \exp\left(\frac{\mu_i - pV_i - \Sigma S_i}{T}\right) \cdot \overbrace{\exp\left(\frac{(1-\alpha) S_i \Sigma}{T}\right)}$$

V_k and S_k are eigenvolume and eigensurface of hadron of sort k

Advantages

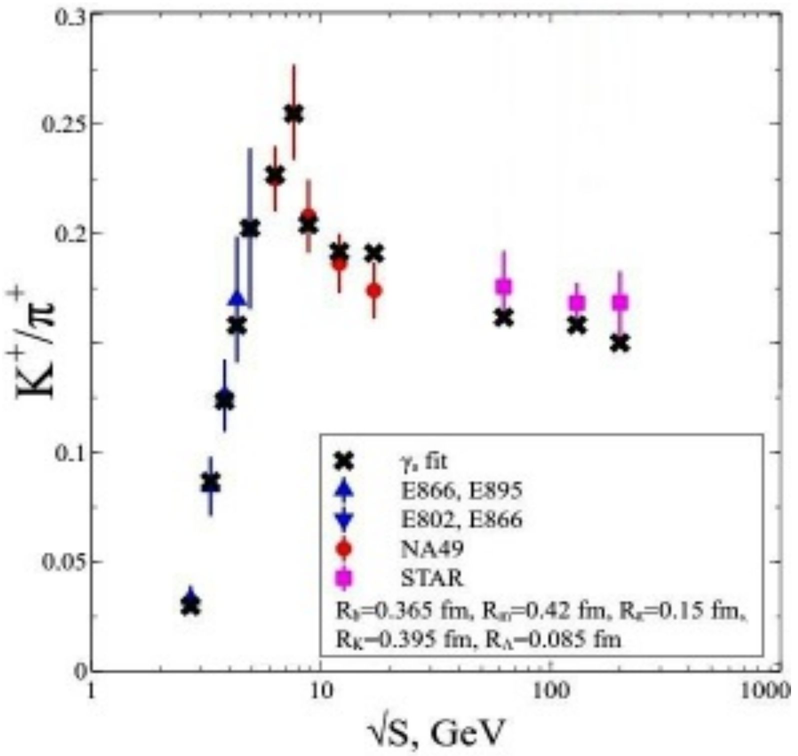
1. It allows one to go beyond the Van der Waals approximation, since it reproduces 2-nd, 3-rd and 4-th virial coefficients of the gas of hard spheres for α = 1.245.

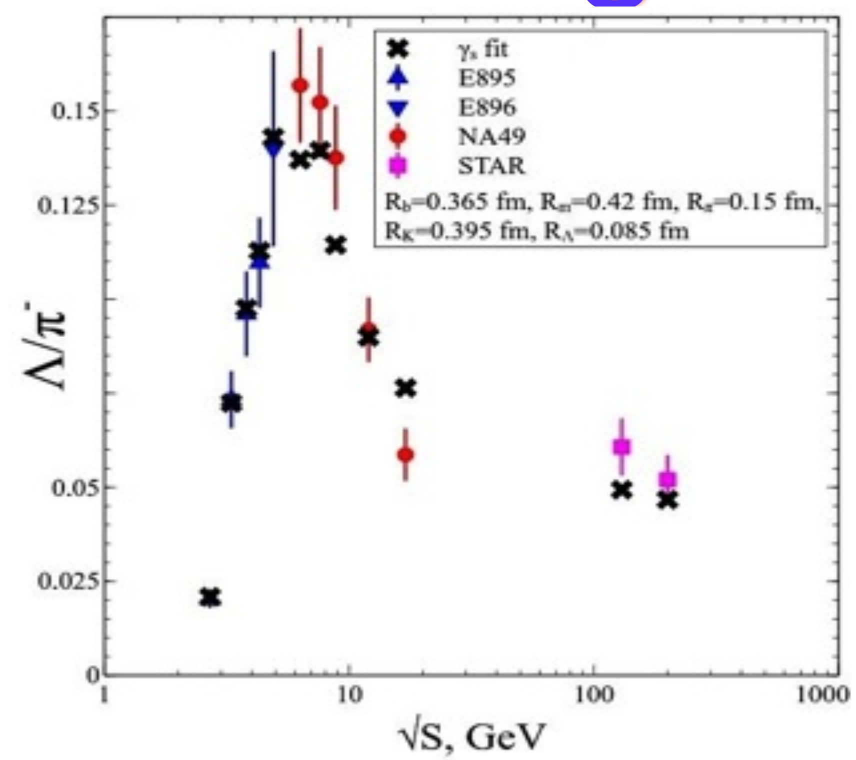
2. Number of equations is 2 and it does not depend on the number of different hard-core radii!

V.V. Sagun, K.A.Bugaev, A.I. Ivanytskyi, D.R. Oliinychenko, EPJ Web Conf 137 (2017);

K.A.Bugaev, V.V. Sagun, A.I. Ivanytskyi, E. G. Nikonov, G.M. Zinovjev et. al., Nucl. Phys. A 970 (2018) 133-155

Most Problematic ratios at AGS, SPS and RHIC energies



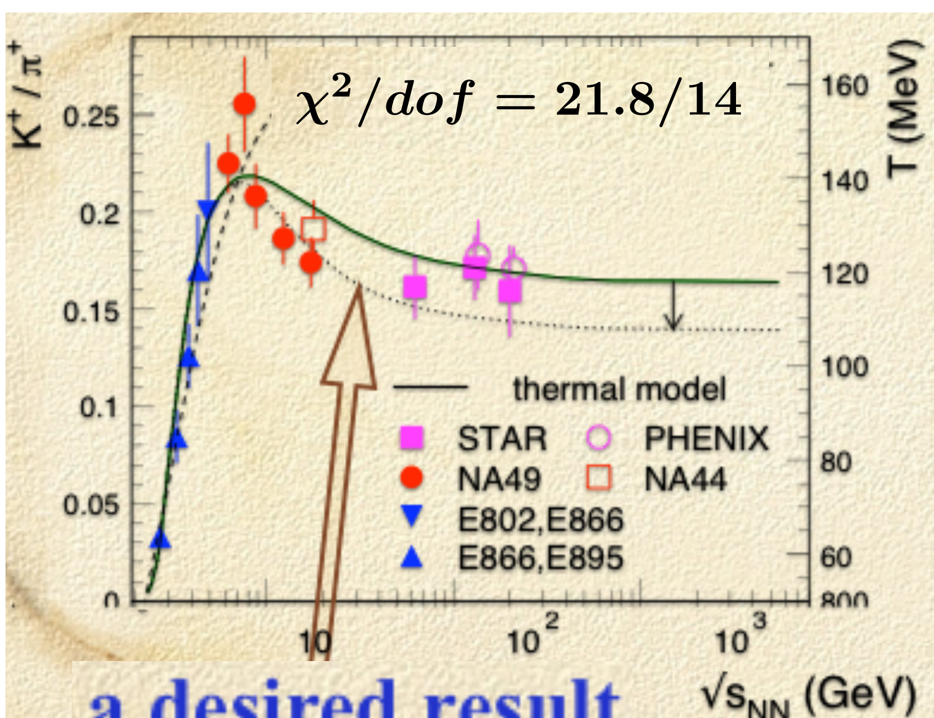


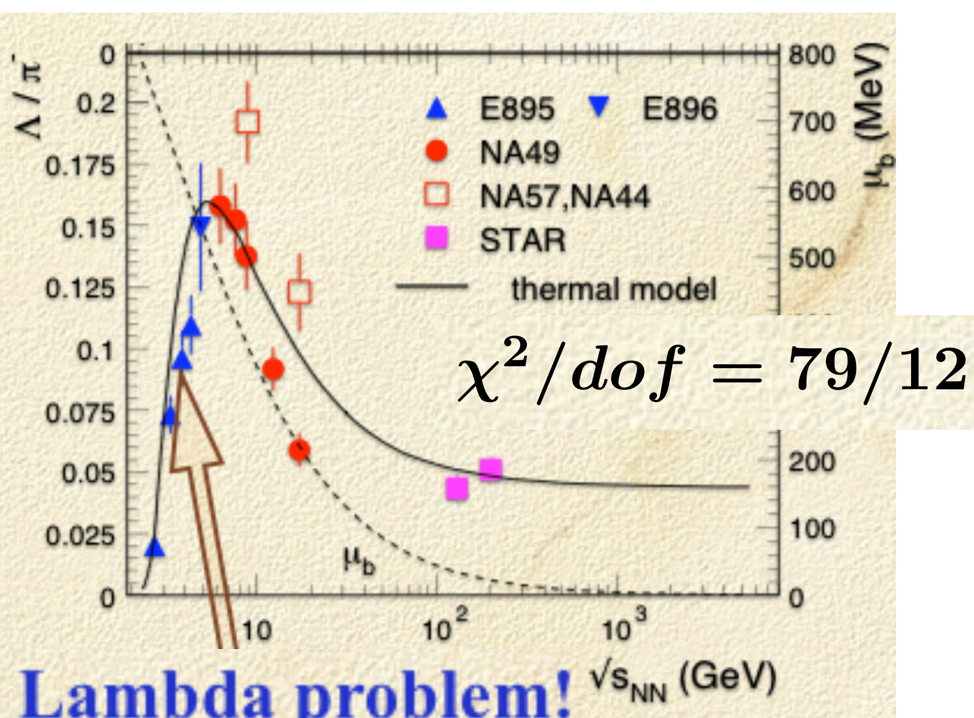
IST EOS: $\chi^2/dof \simeq 3.29/14$ $\qquad$ $\chi^2/dof \simeq 11.62/12$

KAB et al., Nucl. Phys. A 970 (2018)

Note: RHIC BES I data have very large error bars and hence, are not analyzed!

Our IST EOS has 3 or 4 more fitting parameters compared to usual HRGM!



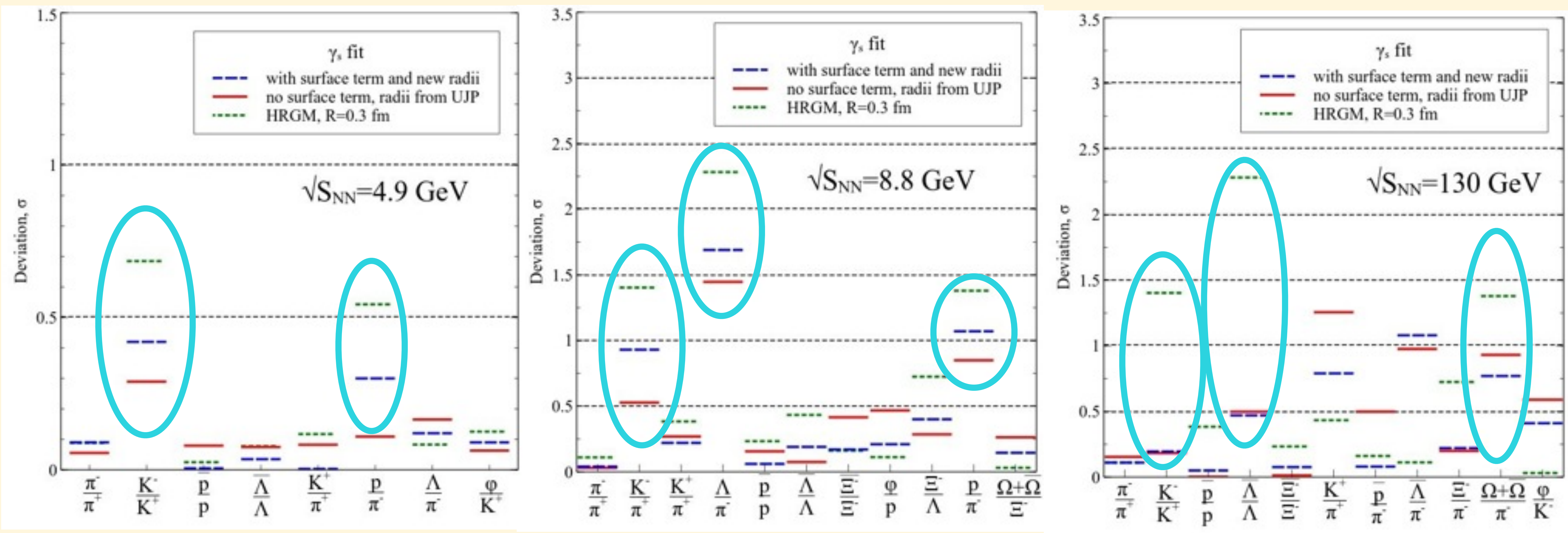


Conventional one component HRGM by PBM and Co:

A. Andronic, PBM, J. Stachel NPA (2006), PLB (2009)

Examples of Hadron Multiplicity Ratios for IST, Multicomponent and One component Van der Waals EoS (2018)

V.V. Sagun et al., Eur. Phys. J. A (2018) 54: 100



Blue bars **IST EoS**

Red bars **Multicomponent Van der Waals EoS**

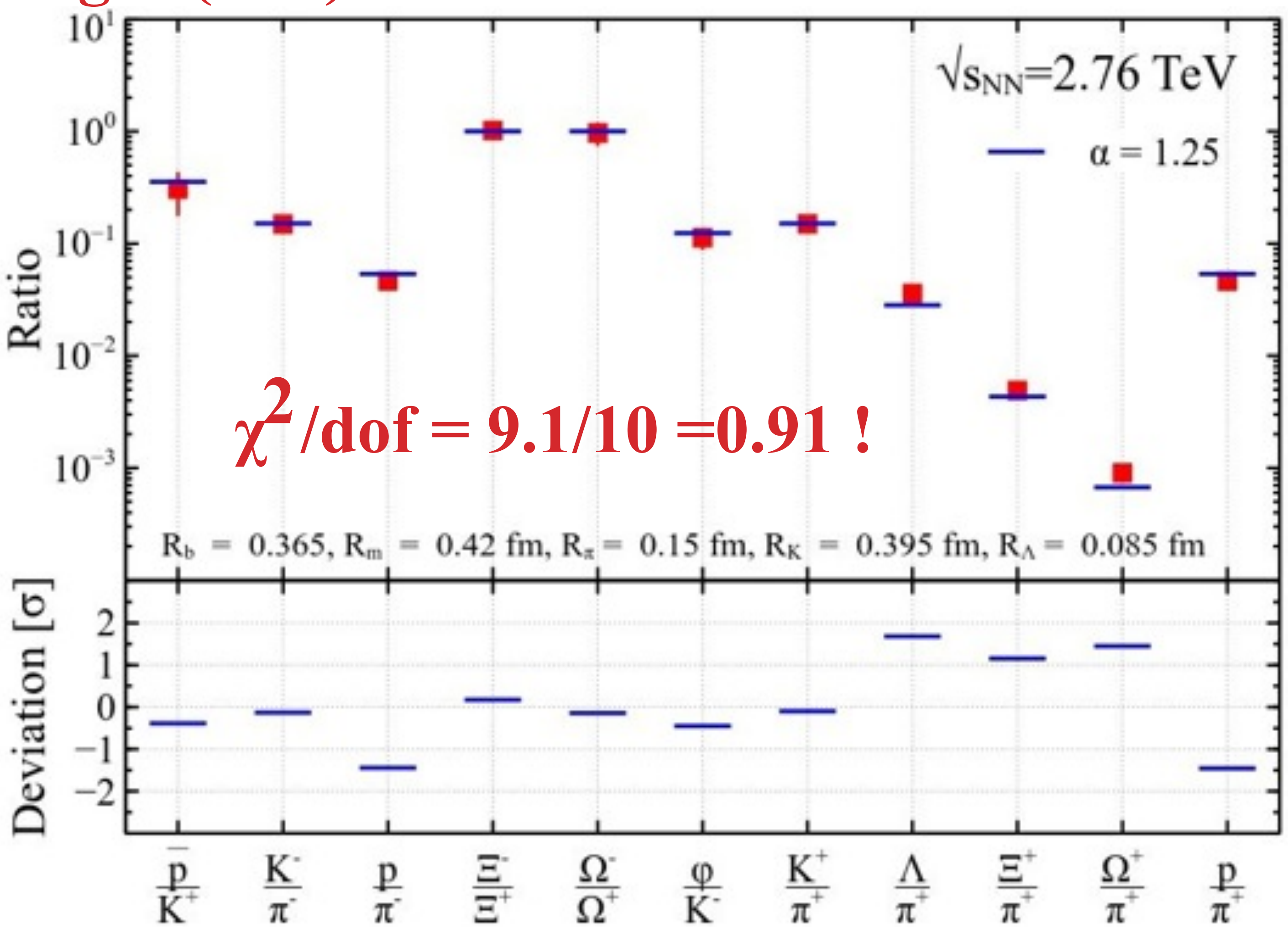
Green bars **One-component Van der Waals EoS (a la P. Braun-Munzinger et al),**

One-component Van der Waals EoS always gives the worst results!

IST EOS Results for LHC energy

Light (anti)nuclei are NOT included into fit

V.V. Sagun et al., Eur. Phys. J. A (2018) 54: 100



Radii are taken from the fit of AGS, SPS and RHIC data => single parameter Tcfo=150+-7MeV

In all our fits (anti)protons and (anti)Ξ-s do not show any anomaly compared to J. Stachel et.al. fit, since we have right physics!

=> There is no proton yield puzzle in a realistic HRGM!

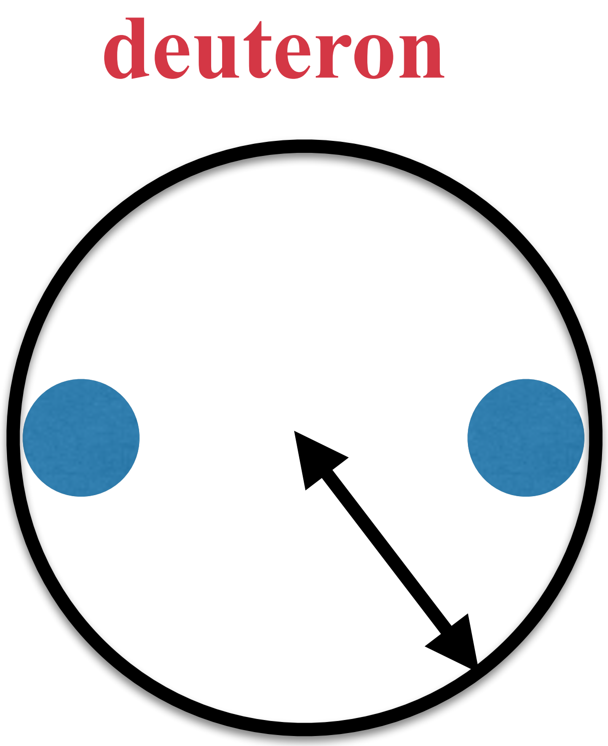
In contrast to J. Stachel, A. Andronic, P. Braun-Munzinger and K. Redlich, J. Phys. Conf. Ser. 509, 012019 (2014) (anti)nuclei are NOT included into the fit!

Combined fit of AGS, SPS, RHIC and LHC data $\chi^2_{tot}/dof \simeq 64.8/60 \simeq 1.08$

Compare with J. Stachel et al. fit quality for Tcfo = 156 MeV χ^2/dof = 2.4 with our one!

BUT the puzzle of light (anti)nuclei remains unresolved!

ALICE Data on Snowballs in Hell: What are Hard-core Radii of Nuclei?



Mean radius of deuteron is large $1.1\sqrt[3]{2} = 1.39$ fm

But hard-core radius of one nucleon is 0.365 +-0.03 fm

=> the deuteron hard-core radius is $0.365\sqrt[3]{A}$ fm

For all loosely bound nuclei of A nucleons

the hard-core radius is $0.365\sqrt[3]{A}$ fm

In J. Stachel, A. Andronic, P. Braun-Munzinger and K. Redlich, J. Phys. Conf. Ser. 509, 012019 (2014)
model the (anti)nuclei have the same hard-core radius as baryons which is unphysical!

ALICE Data on Snowballs in Hell: Is Tcfo of Nuclei Same as of Hadrons?

1. all loosely bound nuclei are frozen together with hadrons =>

$$T_{CFO} \simeq 153 \pm 7\text{MeV} \quad \Rightarrow \quad \chi^2/dof = (9.7+8.7)/(11+8-2) = 18.4/17 \simeq 1.08$$

2. all loosely bound nuclei are frozen separately from hadrons =>

KAB et al., Europhys. Lett. 104 (2013)

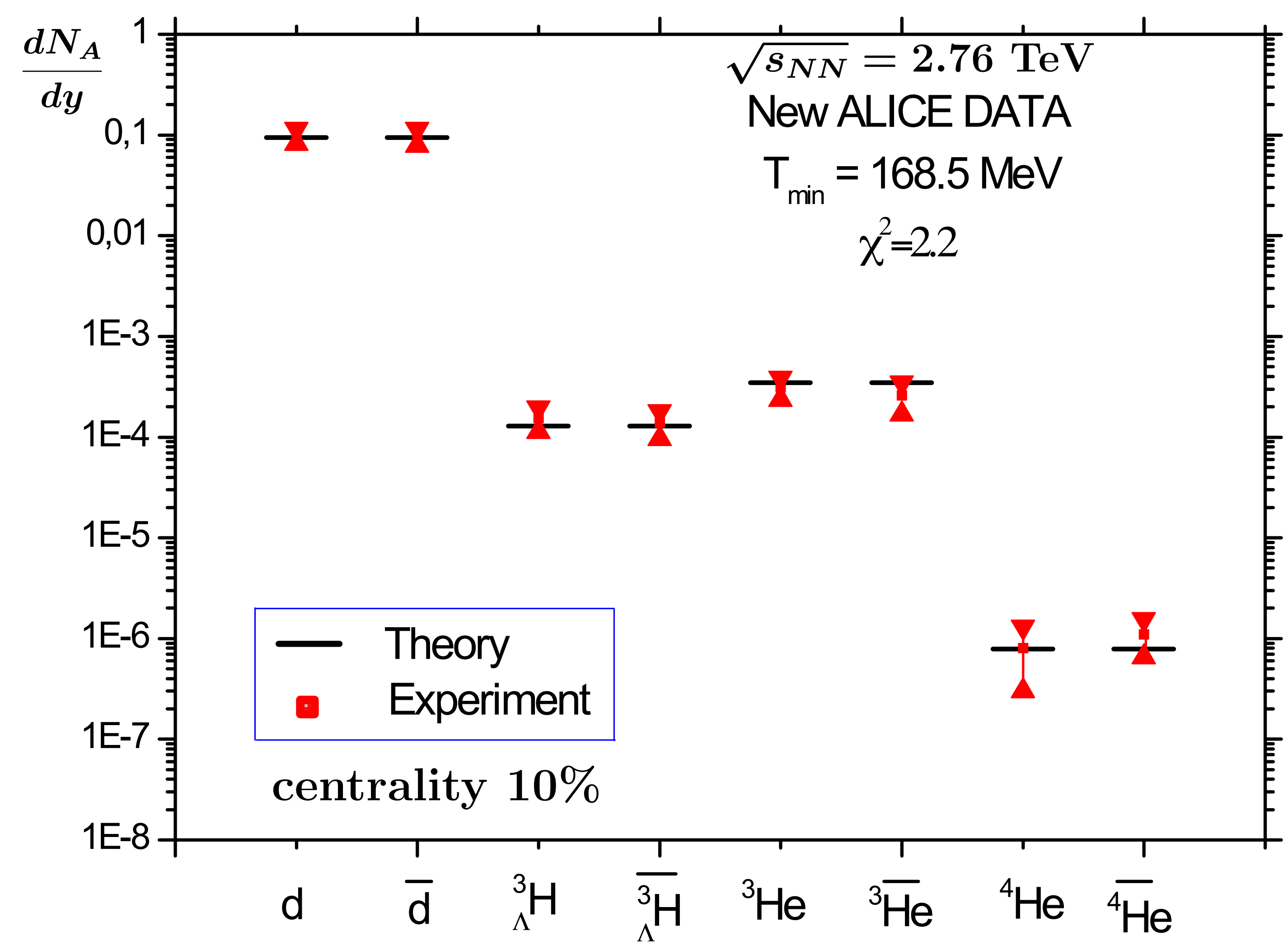
Hadrons $T_{CFO} \simeq 150 \pm 7$ MeV

(anti)Nuclei $T_{CFO} \simeq 168.5 \pm 7$ MeV

$$\chi^2/dof = (9.1+2.2)/(11+8-3) = 11.3/16 \simeq 0.71$$

Remarkable improvement of the fit quality!

But why are the (anti)nuclei frozen at so high temperature?



ALICE Data on Snowballs in Hell: Why Are They Thermalized?

Hagedorn mass spectrum of QGP bags $\frac{dN}{dM} \sim \exp\left[+M/T_H\right]$
is a perfect thermostat and
a perfect particle reservoir! =>
Hadrons born from such bags will be in a full equilibrium!

L. G. Moretto, K. A. B., J. B. Elliott and L. Phair, Europhys. Lett. 76, 402 (2006)

M. Beitel, K. Gallmeister and C. Greiner, Phys. Rev. C 90, 045203 (2014)

Moreover, the analysis of micro canonical partition function of a system containing of 1 Hagedorn bag and N Boltzmann particles shows that at the end of mass spectrum (where it terminates) the temperature depends on the mass of particle and the mass of QGP bag: a few heavier particles will be hotter than many light ones!

L. G. Moretto, K. A. B., J. B. Elliott and L. Phair, Europhys. Lett. 76, 402 (2006)

K. A. B., J. B. Elliott, L. G. Moretto and L. Phair, arXiv:hep-ph/0504011

Conclusions and Perspectives

1. IST EoS provides the most successful fit of hadronic yields from AGS to LHC energies

2. For realistic HRGM there is no proton puzzle at LHC energies!

3. It seems that the light (anti)nuclei freeze-out at higher temperatures than hadrons, if the correct hard-core radii are used

4. In fact, thermalization of light (anti)nuclei can be naturally explained by the existence of QGP bags with the Hagedorn mass spectrum

Thank You for Your Attention!

For a summary of signals of two QCD phase transitions see

K.A. Bugaev et al., arXiv:1801.08605 [nucl-th] and references therein

Table 1. The summary of possible PT signals. The column II gives short description of the signal, while the columns III and IV indicate its location, status and references.

No and Type	Signal	C.-m. energy $\sqrt{s}$ (GeV) Status	C.-m. energy $\sqrt{s}$ (GeV) Status
1. Hydrodynamic	Highly correlated quasi-plateaus in entropy/baryon, thermal pion number/baryon and total pion number/baryon. Suggested in [11, 12].	Seen at **3.8-4.9 GeV** [4, 5]. Explained by the shock adiabat model [4, 5].	Seen at **7.6-9.2 GeV** [4, 5]. Require an explanation.
2. Thermodynamic	Minimum of the chemical freeze-out volume V_{CFO}.	In the one component HRGM it is seen at **4.3-4.9 GeV** [13]. In the multicomponent HRGM it is seen at **4.9 GeV** [14]. Explained by the shock adiabat model [4, 5].	Not seen.
3. Hydrodynamic	Minimum of the generalized specific volume $X = \frac{\epsilon+p}{\rho_b^2}$ at chemical freeze-out.	Seen at **4.9 GeV** [4]. Explained by the shock adiabat model [4, 5].	Seen at **9.2 GeV** [4]. Require an explanation
4. Thermodynamic	Peak of the trace anomaly $\delta = \frac{\epsilon-3p}{T^4}$.	Strong peak is seen at **4.9 GeV** [5]. Is generated by the δ peak on the shock adiabat at high density end of the mixed phase [5].	Small peak is seen at **9.2 GeV** [5]. Require an explanation
5. Thermodynamic	Peak of the baryonic density ρ_b.	Strong peak is seen at **4.9 GeV** [10]. Is explained by min$\{V_{CFO}\}$ [14].	Strong peak is seen at **9.2 GeV** [10]. Require an explanation
6. Thermodynamic	Apparent chemical equilibrium of strange charge.	$\gamma_s = 1$ is seen at **4.9 GeV** [10]. Explained by thermostatic properties of mixed phase at $p = const$ [10].	$\gamma_s = 1$ is seen at $\sqrt{s}$ $\geq$ **8.8 GeV** [10, 13]. Explained by thermostatic properties of QG bags with Hagedorn mass spectrum [10].
7. Fluctuational (statistical mechanics)	Enhancement of fluctuations	N/A	Seen at **8.8 GeV** [9]. Can be explained by CEP [9] or 3CEP formation [10].
8. Microscopic	Strangeness Horn (K^+/π^+ ratio)	N/A	Seen at **7.6 GeV**. Can be explained by the onset of deconfinement at [15]/above [8] **8.7 GeV**.

Present Status of A+A Collisions

In 2000 CERN claimed indirect evidence for a creation of new matter

In 2010 RHIC collaborations claimed to have created a quark-gluon plasma/liquid

However, up to now we do not know:

1. **whether deconfinement and chiral symmetry restoration (ChSR) are the same phenomenon or not?**

2. **are they phase transitions (PT) or cross-overs ?**

3. **what are the collision energy thresholds of their onset?**

Recently the situation gets better!

Recently Suggested Signals of QCD Phase Transitions 2014-2018

During 2013-2017 our group developed a very accurate tool to analyze data

D. Oliinychenko, KAB, A. Sorin, Ukr. J. Phys. 58 (2013)

KAB, D. Oliinychenko, A. Sorin, G.Zinovjev, EPJ A 49 (2013)

KAB et al., Europhys. Lett. 104 (2013)

KAB et al., Nucl. Phys. A 970 (2018)

Most successful version of the Hadron Resonance Gas Model (HRGM)

The high quality description of data allowed us to elucidate new irregularities at CFO from data and to formulate new signals of two QCD phase transitions

D. Oliinychenko et al., Ukr. J Phys. 59 (2014)

KAB et al., Phys. Part. Nucl. Lett. 12 (2015)

KAB et al., EPJ A 52 (2016) No 6

KAB et al., EPJ A 52 (2016) No 8

KAB et al., Phys. Part. Nucl. Lett. 15 (2018)

First work on evidence of two QCD phase transitions

Recently Suggested Signals of QCD Phase Transitions 2016

Our results

1-st order PT of Chiral Symmetry Restoration in hadronic phase occurs at about √s ~ 4.3-4.9 GeV

and 2-nd order deconfinement PT exists at √s ~ 9 GeV

Giessen group results

W. Cassing et al.,, Phys. Rev. C 93, 014902 (2016);
Phys. Rev. C 94, 044912 (2016).

1-st order PT of ChSR in hadronic phase occurs at about √s ~ 4. GeV
and 2-nd order deconfinement PT exists at √s ~ 10 GeV

Hard to locate them due to cross-over in Parton-Hadron-String-Dynamics model!

Higher Virial Coefficients of IST EOS

- Virial expansion of one component EoS with induced surface tension

$$p = nT\Big[1 + \overbrace{4V}^{a_2}\, n + \overbrace{\Big(16 - 18(\alpha-1)\Big)V^2}^{a_3} n^2 + \underbrace{\Big(64 - 216(\alpha-1) + \frac{243}{2}(\alpha-1)^2\Big)V^3}_{a_4} n^3\Big] + \mathcal{O}(n^5)$$

- Second virial coefficient of hard spheres $a_2 = 4V$ is reproduced always

- Fourth virial coefficient of hard spheres

$a_4 \simeq 18.365 V^3 \;\Rightarrow\; \alpha \simeq 2.537,\; a_3 \simeq -11.666 V^2$ - not reproduced

$\alpha \simeq 1.245,\; a_3 \simeq 11.59 V^2$ - reproduced with 16 % accuracy

One parameter reproduces two (3rd and 4th) virial coefficients and allows generalization for multicomponent case

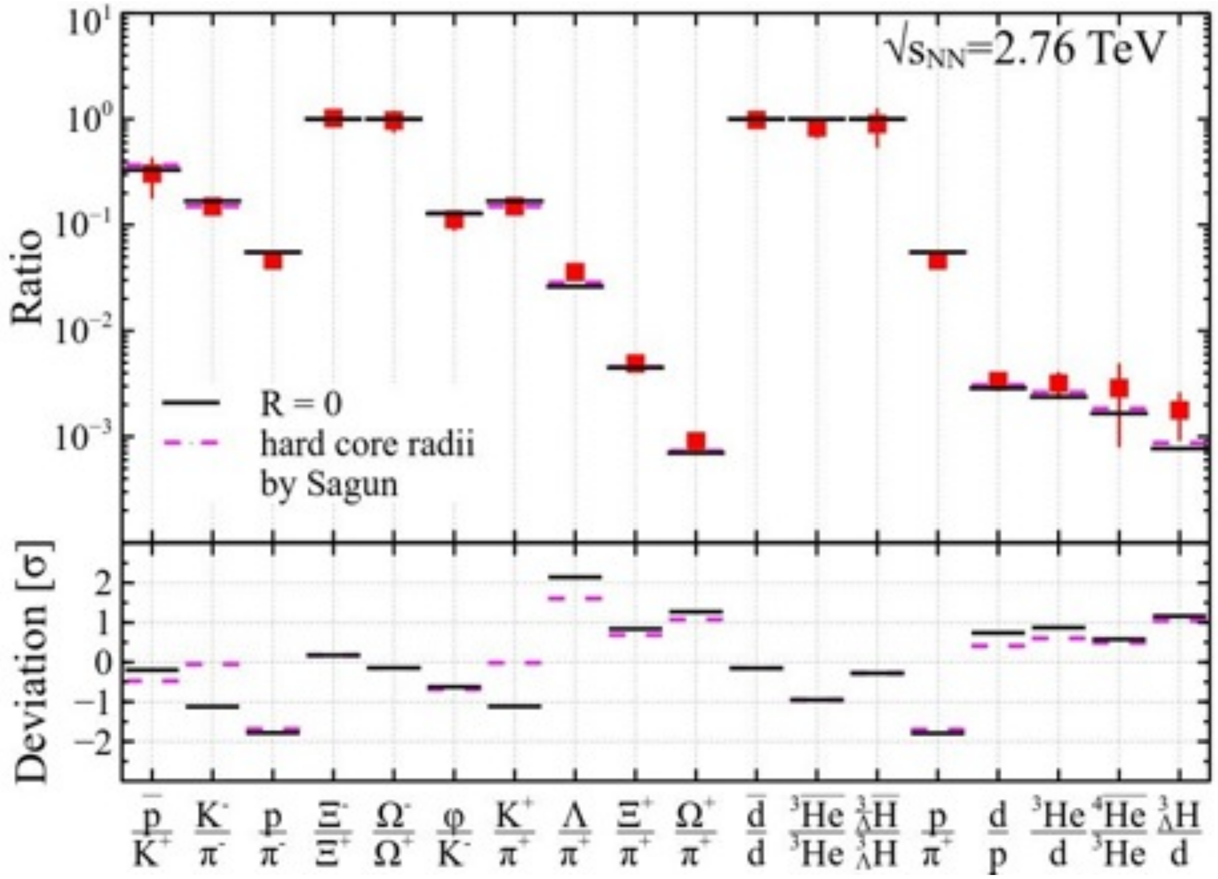
=> IST EoS is valid for packing fractions $\eta < 0.22$

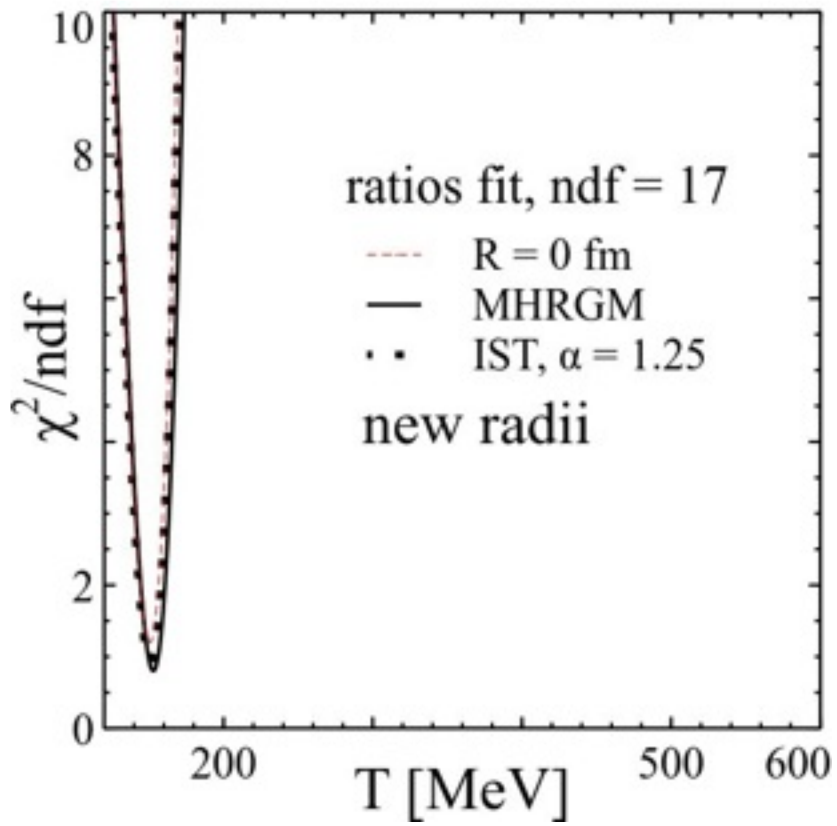
V.V. Sagun, K.A.Bugaev, A.I. Ivanytskyi, D.R. Oliinychenko, EPJ Web Conf 137 (2017);

K.A.Bugaev, V.V. Sagun, A.I. Ivanytskyi, E. G. Nikonov, G.M. Zinovjev et. al., Nucl. Phys. A 970 (2018) 133-155

HRGM Results for LHC energy

Light (anti)nuclei are included into fit





Ideal gas

$T_{CFO} \simeq 151 \pm 7$ MeV

$\chi^2/dof \simeq 17/17 \simeq 1$

Conventional HRGM:

V. V. Sagun, Ukr. J. Phys. **59**, 755 (2014)

R_π=**0.10 fm**, R_K=**0.395 fm**, R_Λ=**0.11 fm**, R_b=**0.355 fm**, R_m=**0.40 fm**

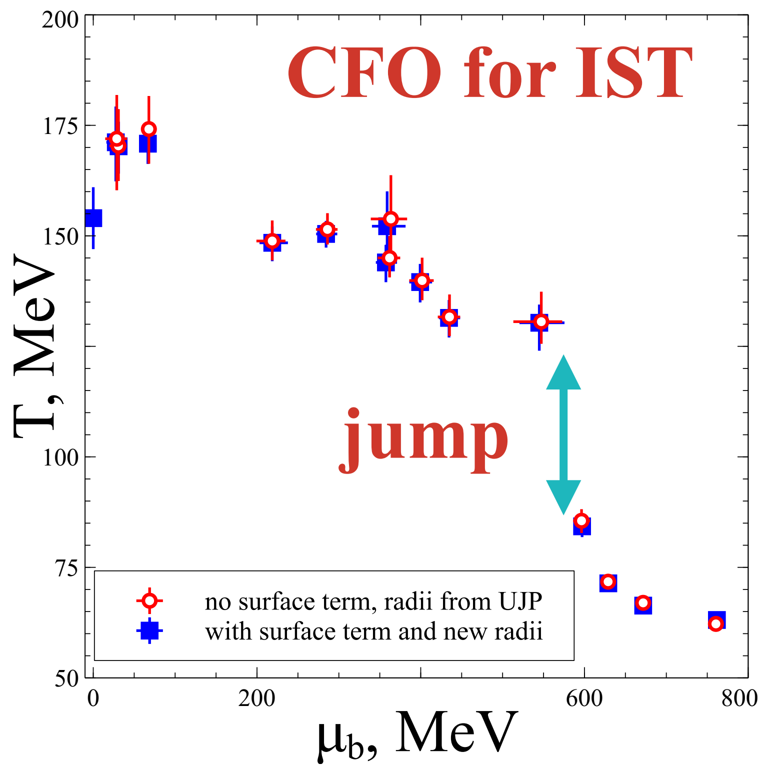
$T_{CFO} \simeq 153 \pm 7$ MeV

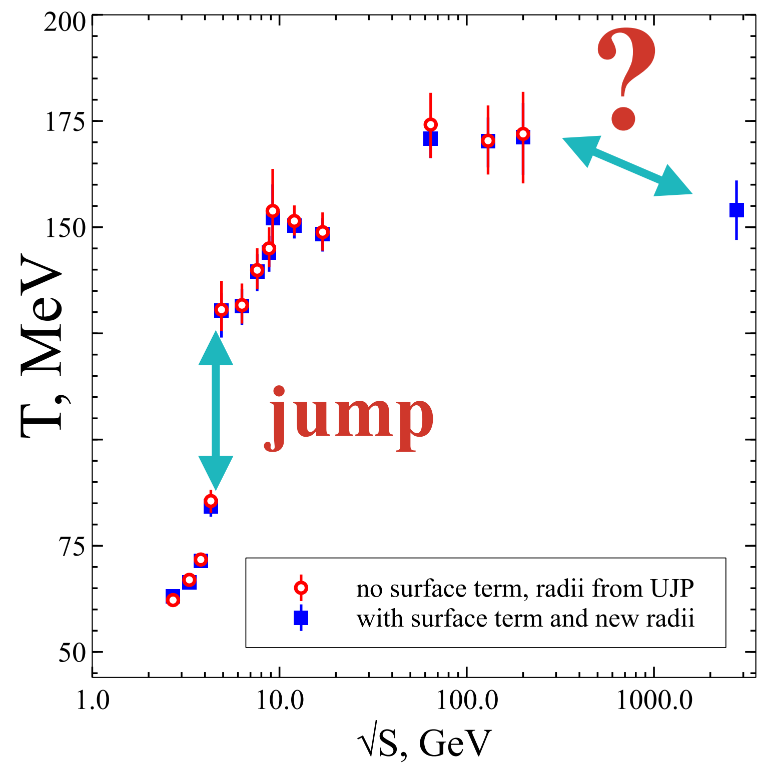
χ^2/dof = 13.58/17 =0.8 !

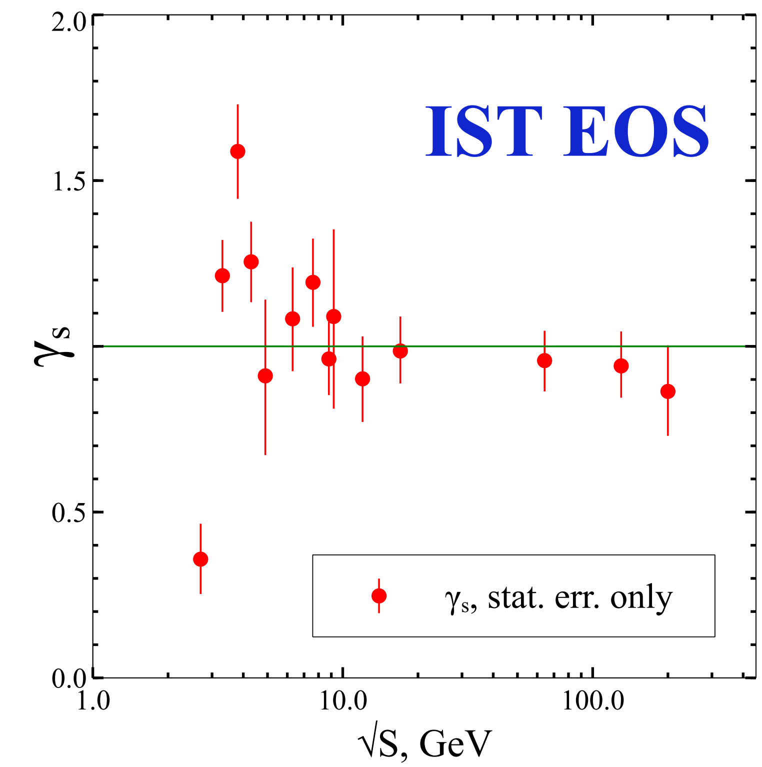
Similar to J. Stachel, A. Andronic, P. Braun-Munzinger and K. Redlich, J. Phys. Conf. Ser. 509, 012019 (2014) (anti)nuclei have the same hard-core radius as baryons which is unphysical!

Compare J. Stachel et al. fit quality for Tcfo = 156 MeV χ^2/dof = 2.4 with our one!

Main Results for AGS, SPS and RHIC energies







IST EOS (without ALICE):

R_π=0.15 fm, R_K=0.395 fm, R_Λ=0.085 fm, R_b=0.365 fm, R_m=0.42 fm

Only pion and Λ hyperon radii are changed a bit, but no effect on T and μ_B

1. **We confirm that there is a jump of T_{CFO} between √s = 4.3 GeV and √s = 4.9 GeV**

2. **We confirm that there is a strangeness enhancement peak at √s = 3.8 GeV**

3. **Why Tcfo at LHC is lower than at highest RHIC energy???**

V.V. Sagun et al., NPA (2018) and arXiv:1703.00009 [hep-ph]